

# Modeling lithium rich carbon stars in the Large Magellanic Cloud: an independent distance indicator ?

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## ABSTRACT

We present the first quantitative computations explaining the presence in the Large Magellanic Cloud of some AGB stars which share the properties of being Carbon stars (surface  $C/O > 1$ ) and Lithium rich. A self-consistent description of time-dependent mixing, overshooting and nuclear burning was required. The products of nucleosynthesis at the stellar surface turn out to be very sensitive to the temperature at the base of the outer convective envelope ( $T_{bce}$ ) during the quiescent phase of hydrogen burning. Lithium production is obtained for  $T_{bce} \geq 4 \cdot 10^7 K$  (Hot Bottom Burning), but  $T_{bce} \geq 6.5 \cdot 10^7 K$  is necessary to cycle into Nitrogen the carbon previously convected to the stellar surface by the third dredge up. Therefore, Li-rich C stars can occur for  $T_{bce}$ 's in this small range of temperatures. We then identify a possible -narrow-range of masses and *luminosities* for this peculiar evolutionary stage. Comparison of these models with the luminosities of the few Li-rich C stars in the LMC provides an independent distance indicator (within  $\sim 0.25\text{mag}$ ) for the LMC. Present data and models are consistent with  $(m - M)_0 \sim 18.7$ , but a better determination would be possible by refining the observations and the theoretical models.

*Subject headings:* stars: evolution, AGB and post-AGB, carbon

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## 1. Introduction

Spectroscopic analysis in the Magellanic Clouds (Smith & Lambert 1989, 1990) showed the presence of high-luminosity, lithium rich AGB stars, having surface Li abundances orders of magnitude larger than commonly observed in galactic giants. The presence of Li is well explained in the framework of “hot bottom burning” (HBB), as suggested by Cameron and Fowler (1971). Models coping with this problem must employ non instantaneous mixing: in fact, the Cameron–Fowler mechanism is based on a nuclear time scale for Li and Be–burning shorter than that of mixing (Sackmann & Boothroyd 1992). Our code, ATON2.0, has been recently implemented with an algorithm coupling nuclear burning and time–dependent chemical mixing (and overshooting, if any), allowing it to successfully deal with the above problem (Ventura et al. 1998; Mazzitelli, D’Antona & Ventura 1999).

In this paper we focus our attention on Carbon stars (C stars) in the LMC that exhibit also large Li abundances at their surfaces (Richer, Olander & Westerlund 1979, Smith, Plez & Lambert 1995), since the co–existence of C and Li is unexpected on theoretical grounds. In fact, the Hot Bottom Burning (HBB) conditions required to ignite Li production should lead to fast CNO processing at the base of the envelope, with subsequent destruction of the  $^{12}\text{C}$  previously convected to the surface during the third dredge–up. We show that there is a narrow range of stellar masses in which, despite the activation of the Cameron–Fowler mechanism, carbon can survive long enough in the convective envelope to keep the C/O ratio over unity, although the  $^{13}\text{C}/^{12}\text{C}$  ratio increases. For a non negligible fraction of their AGB life, these ob-

jects can be then observed as Li–rich C stars.

## 2. The Models

The main features of the ATON2.0 code are described in Ventura et al. (1998). Here we only mention the main updates in the macrophysical inputs. Even if some convective overshooting is included in the present models, convection as a whole is addressed in a purely local frame. The formal convective boundaries are thus fixed according to the Schwarzschild criterion. The convective fluxes inside the instability regions follow the full spectrum of turbulence (FST) model of convection, in the form given by Canuto, Goldman & Mazzitelli (1996), to account for the non–linearities in the growth rates. Fine tuning of the  $\beta$  parameter in FST model is not necessary in this context, since we know that also a variation by 50% does not show any important effect upon lithium production (Mazzitelli et al. 1999), at variance with the results obtained by the mixing length theory (MLT) (Sackmann & Boothroyd 1992, 1995).

Lithium production can be modeled only by adopting a time–dependent approach, in which nuclear burning and mixing of chemicals are self–consistently coupled. In our code, this goal is accomplished by solving a diffusive equation that is valid for any chemical species. In our algorithm, the terms relative to nuclear evolution and mixing are treated simultaneously: the approximation of dealing separately with each of them would lead, in the present case, to a vanishingly small abundance of Li (Mazzitelli et al. 1999).

Our scheme of overshooting from the convective regions (Ventura et al. 1998) is based on an exponential decay of the mean turbulent velocity outside the convective bound-

aries, in the form:  $u = u_b \cdot \exp(\frac{1}{\zeta f_{thick}} \ln \frac{P}{P_b})$  where  $u_b$  and  $P_b$  are the velocity and pressure at the convective boundary,  $P$  is the local pressure, and  $\zeta$  is a free parameter measuring the extent of the overshooting region. Moreover,  $f_{thick}$  is the thickness of the convective region in units of the pressure scale height  $H_p$  (maximum allowed value = 1), and this avoids overshooting regions larger than the entire convective zone. This treatment of overshooting is not much different from the one adopted by Herwig et al. (1997); it is also consistent with the results of numerical two-dimensional hydrodynamic simulations by Freytag, Ludwig & Steffen (1996). In the present work, being interested to investigate the properties of carbon stars, we assumed both overshooting from above and below convective regions, and the value of the parameter  $\zeta$  has been set equal to 0.02, in agreement with previous works.

### 3. Lithium production and carbon stars

The most luminous AGB stars in the Magellanic Clouds are Li-rich (Smith & Lambert 1989, 1990), consistent with the mechanism of Li production by HBB hypothesized by Cameron & Fowler (1971). For  $T \geq 4 \cdot 10^7 K$ , the reaction  $^3He + ^4He \rightarrow ^7Be$  becomes efficient on the timescale of AGB evolution. Beryllium can then capture one more proton or decay into lithium. In this latter case, the mixing time scale is such that, in a dynamical equilibrium, some lithium is produced far from the base of the envelope. Here it survives due to the low temperatures and can eventually reach the surface. Independently of the above process, carbon stars form as a consequence of the penetration of the convective envelope into inner layers, following each thermal pulse (TP). Primary carbon is dredged up

to the surface until the C/O ratio grows larger than unity. C stars are usually observed at lower luminosities than Li-rich AGBs, since, for large temperatures at the base of the convective envelope, the CNO cycle becomes so efficient that carbon is turned into nitrogen faster than it is dredged up.

This is suggested both by computations and by observations showing that practically all C stars are less luminous than Li-rich stars in the Magellanic Clouds. A recent survey by Plez, Smith & Lambert (1993) has however confirmed the presence of Li-rich C stars. Also in our Galaxy a few Li-rich C stars are known (Wallerstein & Conti 1969; Abia et al. 1991): they seem to be among the most luminous C stars, but their distance determinations are not so certain. On the other hand, some Magellanic Clouds Li-rich C stars are certainly among the most luminous C stars, just below the O-rich, Li-rich AGB stars (Smith et al. 1995).

Our aim was then to investigate a theoretical framework in which the coexistence of C and Li-rich stars is allowed. We focused our attention on masses  $M \leq 4M_\odot$ . The tracks were computed with a metallicity appropriate to the Large Magellanic Cloud, namely  $Z=0.01$ . Mass loss has been modelled according to Blöcker (1995), with  $\dot{M} = \dot{M}_R \cdot L^{2.7}/M^{2.1}$ , being  $\dot{M}_R$  the usual Reimer's mass loss rate. In this latter, the free parameter  $\eta$  has been set to 0.05, since this value seems to fit the lithium vs. luminosity trend observed in the Magellanic Clouds AGB stars (Ventura, D'Antona & Mazzitelli 1999).

Fig.1 shows the physical and chemical evolution of a  $4M_\odot$  sequence. The trend of the run luminosity vs. time after the first five pulses, is different from the case when overshooting from below the bottom of the con-

Fig. 1.— Variation with time of the physical and chemical properties of a  $4M_{\odot}$  model of metallicity  $Z = 0.01$  during the AGB phase of thermal pulses. Left panels show the evolution of luminosity and of the temperature at the base of the convective envelope, right side panels report the changes in surface Li and C/O.

vective envelope is neglected. The explanation is in the deeper diffusion of chemicals, which mixes up in the envelope helium produced by the H-burning shell. A detailed analysis of the mechanism, and of the differences encountered on the AGB when applying the two different schemes of complete, instantaneous overshooting, and the diffusive, time-dependent one, can be found in Mazzitelli et al. (1999).

Let us now examine the evolution of chemicals at the surface of the star. We first see an increase in the C/O ratio following each pulse, due to an early onset of the third dredge-up. At the same time, the Cameron-Fowler mechanism ignites and the lithium abundance, which had previously dropped to  $\log[\epsilon(^7\text{Li})] \sim -2$  (where  $\log[\epsilon(^7\text{Li})] = \log(^7\text{Li}/H) + 12$ ), starts rising. At the third pulse the star already shows up as Li-rich, but it never becomes a C star since CNO burning grows more and more efficient at the base of the envelope. This is seen in the right lower panel of fig.1, where a severe drop of the C/O ratio following the H-shell re-ignition after each pulse is evident. From these results, we conclude that C stars can not be produced or survive when  $T_{bce} \geq 6.5 \cdot 10^7 K$ . At variance, the Cameron-Fowler mechanism starts leading to detectable surface lithium abundances already at  $T_{bce} \sim 4 \cdot 10^7 K$ . There is then a

narrow range of  $\delta T_{bce} \sim 2.5 \cdot 10^7 K$  in which, in principle, both C and Li can show up at the surface, if the third dredge-up is already efficient. It is then likely that the observed Li-rich C stars in the Magellanic Clouds have  $T_{bce}$ 's falling in this range.

Consider now the evolution of smaller masses, namely  $M/M_{\odot} = 3.8, 3.5$  and  $3.3$ , for the same metallicity. The results are shown in fig. 2. The  $3.8M_{\odot}$  track starts showing large lithium abundances shortly after the C/O ratio exceeds unity but, after one more TP, hot bottom burning becomes effective in depleting carbon. The ratio  $^{13}\text{C}/^{12}\text{C}$  during the evolution rises to  $\sim 0.4$ , thus this object has the characteristics of a J-type star. From fig.2, one can conclude that the star is a Li-rich C star for  $\sim 30000$  years.

Fig. 2.— Variation with time of the luminosity,  $T_{bce}$ , Li abundance and C/O ratio in three intermediate mass models of different masses during the phase of thermal pulses.

The track for the  $3.5M_{\odot}$  star is the most suitable to fit the observational constraints of being both C- and Li-rich.  $T_{bce}$  rapidly grows hot enough to ignite lithium production but, before the CNO cycle takes over, one has to wait for  $\sim 2 \cdot 10^5$  yr. Moreover, shortly after the ignition of CNO burning at the base of the envelope, mass loss is so efficient that it works as a thermostat, and the C/O ratio does not decrease any more. This is confirmed by the drop of the total luminosity and of the temperature at the base of the convective envelope of the star shown in fig.2. The track was stopped when the total mass of the star was slightly lower than  $1.4M_{\odot}$  during which time lithium was also decreasing. Here again the  $^{13}\text{C}/^{12}\text{C}$  ratio is  $\sim 0.24 - 0.3$  during the Li-rich phase.

Lastly, we discuss the track for the  $3.3M_{\odot}$  star. This case looks similar to the Li-production mechanism discussed by Iben (1973).  $T_{bce}$  never grows large enough to ignite the Cameron-Fowler mechanism, and the star never produces lithium, except for short periods during TP's: following the peak of the pulse, the external envelope penetrates inwards, and convective eddies reach sufficiently hot regions to ignite  ${}^3\text{He}$  burning, which in turn triggers beryllium production, which then decays into lithium in the envelope. At the same time more  ${}^{12}\text{C}$  is convected to the surface of the star. Afterwards, lithium production ends, but lithium survives then in the envelope until the H-burning shell resumes,  $T_{bce}$  grows again to  $\geq 10^7\text{K}$ , a temperature not sufficient to provide  ${}^3\text{He}$  burning, but large enough to destroy lithium. For lower masses, not only is lithium more severely depleted in pre-AGB phases, but the efficiency of the third dredge-up does not allow for both C- and Li-rich structures. The evolution shows no sign of a  ${}^{13}\text{C}/{}^{12}\text{C}$  increase.

The above results illustrate the following:

1) there might be (rarely) Li-rich C stars in the middle of the O-rich Li-rich AGBs which populate the  $M_{bol}$  range between -6 and -7. In particular, the  $3.8M_{\odot}$  evolution presented here shows that for a relatively short lifetime this mass could show up as a Li-rich C star also rich in  ${}^{13}\text{C}$  at  $\log L/L_{\odot} \simeq 4.5$ , that is at  $M_{bol} = -6.5$ . Incidentally we note that Crabtree, Richer & Westerlund (1976) have discovered in the LMC such a luminous atypical Li-rich C star.

2) stars such as the  $3.5M_{\odot}$  one present quite a long evolutionary stage, in which they can be observed as Li-rich C stars. Their luminosity should be  $\log L/L_{\odot} \simeq 4.2 - 4.28$  (namely  $M_{bol} = -5.75 - -5.95$ ). The most

luminous Li-rich C stars *below* the boundary of  $M_{bol} = -6$  observed in the LMC are then likely to fall within this range; they should also be J stars, being very rich in  ${}^{13}\text{C}$ . There are three such objects, listed in the Smith et al. 1995 paper, with  $M_{bol}$  ranging from -5.5 to -5.7, based on a distance modulus  $(m-M)_0 = 18.6$ . If we take these numbers at face value, a distance modulus  $(m-M)_0 \sim 18.7$  would give the best match between our models and the observations. However, the errors on the observed absolute bolometric magnitudes are certainly too large (at least  $\pm 0.2 - 0.3\text{mag}$  according to Smith et al. 1995) to draw strong conclusions. Nevertheless, the range of masses and luminosities for which the HBB conditions required to produce Li-rich C stars are fulfilled is so small that, given sufficiently accurate theoretical models (see discussion in section 4), *a better determination of the observational magnitudes, and possibly an enlarged sample of such stars could constitute a powerful, independent way of determining the LMC distance, an important intermediate benchmark to the distance scale of the Universe.* A similar suggestion was advanced earlier by Plez et al. (1993), who proposed to use the O-rich Li-rich AGBs having  $M_{bol}$  between -6 and -7. The present suggestion may lead to a more accurate determination of distance, in view of the smaller range of magnitudes of these stars.

3) In the context of our modeling it is *not* possible to give a satisfactory explanation for the Li-rich C stars of  $M_{bol} \sim -4.5$  ( $\log(L/L_{\odot}) \sim 3.8$ ). There are three such stars in Smith et al. (1995), and three also in the M31 survey of C stars by Brewer, Richer & Crabtree (1996), and all of them are J stars. If these stars belong to the evolution of the  $3.5M_{\odot}$  stars, they can be at such a low lumi-

osity only for  $\sim 6\%$  of the time (during the lowest luminosity phase of the TPs). In this case, there should be  $\sim 15$  Li-rich C stars at  $M_{bol} \sim -5.7$  for each star at  $M_{bol} \sim -4.6$ . These stars are just not observed and would not have been missed in the quoted surveys.

On the other hand, stars following the  $3.3M_{\odot}$  evolution could show up as Li-rich C stars for short periods. However, these stars should *not* be J stars, as  $^{13}\text{C}$  is not enhanced in our computations. We leave this problem open.

#### 4. The theoretical luminosity range of Li-rich C stars

To first order, the luminosity at which the  $T_{bce}$  needed to ignite lithium production is reached is not very dependent on the convective model adopted, as shown by Mazzitelli et al. (1999) for Li-rich O-rich AGB modeling. The effect of changing the convection model and overshooting is mainly to shift the mass range over which Li-rich O-rich stars appear, but the luminosity range at which this occurs is very similar: we have verified this coincidence within  $\sim 0.1$  mag. Also, the above quantities do not vary if, in modeling overshooting, we change the e-folding distance of decay of velocity outside the convective regions (consistently with early onset of the third dredge-up). The same reasoning can be applied to the Li-rich C stars. Nevertheless, however, a wide exploration of physical parameters (chemical composition, opacities, convective model, mass loss rate) would be needed to determine the theoretical dependence of the luminosity range of Li-rich C stars to better than 0.1 mag. Of course, we did not take into account effects such as the difference between upward and downward convective flows, eddy transport over scales

large compared to the scale of diffusive mixing assumed in the FST theory, etc. In practice, from a theoretical point of view, much more work is needed to allow use of Li-rich C stars as a good distance indicator.

#### 5. Conclusions

In this paper, we present and discuss the first truly evolutionary models successfully reproducing the status of Li-rich C stars. We find that this modeling is made possible by a small difference between the temperatures required to ignite the Cameron-Fowler mechanism leading to lithium production, namely  $T_{bce} \sim 4 \cdot 10^7 K$ , and the one required to destroy carbon by CNO fusion, that is:  $T_{bce} \sim 6.5 \cdot 10^7 K$ . We conclude that the Li-rich C stars in the Magellanic Clouds have temperatures at the base of their convective envelopes within the range identified by the two above values. Although much wider modeling will be needed to check the uncertainties, this result is at first order independent of some of the macro-physical input, like the convective model and the extent of the overshooting region. *The range of luminosities in which this process may take place is very small:  $\log L/L_{\odot} \simeq 4.2 - 4.28$ , namely  $M_{bol} \simeq -5.75 - -5.95$ : thus the luminosity of Li-rich C stars can become an interesting independent method of determining the LMC distance modulus if we succeed in refining the observations and the theoretical models.*

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